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STUDY OF HYDRAULIC SYSTEM COMPONENT STORAGE WITH A RUST INHIBITED BARIUM FREE DEVELOPMENT HYDRAULIC FLUID CANDIDATE

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14. ABSTRACT
METSS Corporation, under a Small Business Innovation Research program (F33615-96-C-5074) with AFRL/MLBT, developed a hydraulic fluid candidate known as METTS HyTherm CI-2. This fluid is intended to be rust inhibited, barium free, thermally stable and fire resistant hydraulic fluid suitable for aircraft use. METSS HyTherm CI-2 would eliminate the need for a separate storage fluid for components. The currently used storage fluid is classified as hazardous waste due to the barium additives. The METTS HyTherm CI-2 fluid was contaminated with distilled water and stored in jars containing bearings and pistons in a controlled environment. Each jar was inspected once a year for three years. At the end of the storage period, the METTS HyTherm CI-2 fluid was endurance pump tested.
The METSS HyTherm CI-2 fluid excelled in all storage tests as well as the pump endurance test. There was no corrosion present after three years of storage and pump performance was comparable with the pump performance with fluid MIL-PRF-83282 used in earlier study.

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Study of Hydraulic System Component Storage with a Rust Inhibited Barium Free Developmental Hydraulic Fluid Candidate

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ABSTRACT

METSS Corporation, under a Small Business Innovative Research program with AFRL/MLBT, developed a hydraulic fluid candidate known as METSS HyTherm CI-2. This fluid is intended to be rust inhibited, barium free, thermally stable and fire resistant hydraulic fluid suitable for aircraft use. METSS HyTherm CI-2 would eliminate the need for a separate storage fluid for components. The currently used storage fluid is classified as hazardous waste due to the barium additives. The METSS HyTherm CI-2 fluid was contaminated with distilled water and stored in jars containing bearings and pistons in a controlled environment. Each jar was inspected once a year for three years. Also, the fluid was stored in a new Eaton Aerospace Corporation model PV3-075-15 aircraft hydraulic pump. Water was added to the pump fluid and the pump was inspected once a year for three years. At the end of the storage period, the METSS HyTherm CI-2 fluid was endurance pump tested.

The METSS HyTherm CI-2 fluid excelled in the all storage tests as well as the pump endurance test. There was no corrosion present after three years of storage and pump performance was comparable with the pump performance with fluid MIL-PRF-83282 used in an earlier study.

EXPERIMENTAL

Existing military hydraulic fluids, MIL-PRF-83282 [1], and MIL-PRF-87257 [2], are thermally stable to 400^{o}F and MIL-PRF-5606 [3] is stable to 275^{o}F. Currently hydraulic fluids used for storage, MIL-PRF-6083 [4] and MIL-PRF-46170 [5] are limited to 225^{o}F upper temperature and therefore have to be drained before components can be installed onto aircraft. The rust inhibitor in MIL-PRF-6083 and MIL-PRF-46170, barium dinonylnaphthalene sulfonate, has caused operational problems when inadvertently left in aircraft [6]. The focus of this program was to prove that hydraulic components could be stored in METSS HyTherm CI-2 without risk of rusting on the shelf and that the pump could subsequently be operated with that same fluid. The METSS HyTherm CI-2 is stable up to 400^{o}F. Real time 3 year storage tests were conducted at ambient laboratory temperature and relative humidity conditions, with water added to some of the jars and to the hydraulic pump. This study was conducted in the same manner as an earlier research effort, the "Study of Hydraulic System Component Storage with Operation and Rust-Inhibited Hydraulic Fluids" [7] [8].

Bearing and Piston in Jar Storage Test

In one set of tests, jars of fluid were used. Two sets of jars were filled with the METSS HyTherm CI-2 test fluid containing 400 ppm of water. In one set of those jars, no metal components were used. In the second set of jars, one 52100 tapered roller bearing (from the Timken Bearing Company) and a used 52100 piston with a bronze alloy shoe (from an F-16 hydraulic pump) were placed inside each jar. A photograph of the setup is located in Appendix A. Contaminating the fluid with water for these storage tests represented severe storage conditions. In a third set of jars, the components were stored after being soaked in the hydraulic fluid containing water and drained for ten seconds. The bearing and piston jar storage test matrix is shown in Table 1.

The bearings were cleaned by a procedure supplied by the Timken Bearing Company. Bearings were brushed thoroughly in hexane and were handled with tongs for the remainder of the cleaning procedure. The bearings were then washed in hot, 125-150˚F, hexane followed by a second wash in fresh hot hexane. Bearings were rinsed twice in a fresh solvent solution containing 90% A.C.S. grade isopropyl alcohol, 9% deionized water, and 1% reagent grade ammonium hydroxide The bearings were placed on clean filter paper to drain; then dried in an oven at 220˚F for 15-30 minutes and stored in a desiccator to cool to room temperature The dry bearings were analyzed by grazing angle Fourier transform infrared microscopy (GA FT-IR) to ensure that residual preservative fluid and organic material had been cleaned from the bearings. The cleaned bearings were photographed, documenting as much surface as possible. The bearings were re-examined and photographed yearly for any visual corrosion.

METSS HyTherm CI-2 was prepared to contain ~400 ppm water. This level of water contamination was selected so that the total water content was approximately 50 ppm below the saturation level for this fluid.

The top of the piston was wetted with fluid by tipping the jar. All jars were capped tightly prior to storage. All specimens were visually examined every month without opening the jars. After each year of storage, one bearing and piston set were removed and inspected from one jar of each set. If corrosion existed, the surface was to be analyzed by grazing angle Fourier transform infrared (GA FT-IR) microscopy. The fluid was examined for debris. Water content was measured in one of the fluid jars for each fluid/water contamination level for years two and three. The first year was not tested for water content due to insufficient fluid.

Pump Storage and Pump Tests

An Eaton Aerospace model PV3-075-15 axial piston pump was filled with METSS HyTherm CI-2 and stored for three years. This pump is a typical axial flow piston pump used in aircraft. Photographs of the pump components before storage can be found in Appendix B. Water, 300 ppm, was added to the METSS HyTherm CI-2 fluid to simulate severe storage conditions. This level of water contamination was selected so that the total water content was approximately 150 ppm below the saturation level for this fluid. Before storage and after every year, the pump was disassembled and the internal parts inspected, changes documented and photographed. Karl Fisher Titration, ASTM D 6403 was used to measure the water level in the test fluid at the yearly inspection. See Table 2 for a list of all test methods used for fluid analysis. If necessary, water was added to return the fluids to their original 300 ppm water concentration. Then the pump was reassembled and returned to storage. At the end of three years, the METSS HyTherm CI-2 stored pump was drained, inspected and refilled with fresh, dry METSS HyTherm CI-2. The post-storage performance of the pump was validated in a 500-hour endurance pump test using the conditions and procedure described below.

<u>Pump Test Conditions</u>:

Pump Shaft Speed:	5000 rpm
Pump Inlet Pressure:	70 psig
Pump Outlet Pressure:	3000 psig
Max Fluid Temperature:	255°F
Pump Outlet Flow:	Cycle between 12.5 gpm and 3 gpm every minute
Test Duration:	500 hours or performance degradation, whichever occurs first.

The test stand was filled with fresh METSS HyTherm CI-2 and any entrained air was bled out. This initial charge of fluid was used throughout the test and no make-up fluid was added. A 50 ml fluid sample was taken at zero hours (immediately following bleeding). The pump was started with a main flow rate of 3 gpm and the speed increased to 5000 rpm. Within one minute the automatic throttling valve cycling was activated to alternate the main flow between 12.5 and 3 gpm every minute. The maximum case drain temperature was stabilized to 250-255°F. Fluid samples were taken at 50 and 100 hours and at every 100-hour increment thereafter. At 500 hours, a 150 ml fluid sample was taken and the test stopped. The pump was disassembled, inspected, and photographed. The two filter elements and the remaining fluid from the test were retained for future reference.

RESULTS

Fluid Only Jar Storage

The water level fluctuated between the second and third year inspections, decreasing after two years and increasing after three years. Rust inhibitor additives generally absorb water so the behavior after two years was unexpected and unexplained See Table 1 for the water content data.

Bearing and Piston Jar Storage

The bearing and piston sets stored in METSS HyTherm CI-2 and the dip and drain sets exhibited no evidence of corrosion throughout the 3-year period of testing, however, one bearing and piston set stored in METSS HyTherm CI-2 formed some gel on the bearing and bottom of the jar after 3 years of continuous storage. There was no change in fluid appearance in any of the jars. Water content was not measured in the first year of this study due to the limited amount of fluid available for make up. See Table 1 for the water content of the jars containing fluid, a bearing and a piston.

Pump Storage

METSS HyTherm CI-2 pump inspection after one year of storage

No corrosion of any internal surfaces was noted and all parts had an appropriate new luster. A few gel deposits, not readily seen with the heavily wetted surfaces of the freshly opened pump, became obvious as the parts drained for photographic documentation. The gel color was identical to the fluid color, and the shape these soft gel deposits tended to take the form of the crevices they resided in or on. The largest deposit was found on the face of the cylinder block. The corrosion free condition of the internal components can be seen in Appendix C. The pump was reassembled to proper specifications including internal lock-wire installation. Analysis of the fill fluid from the pump showed water content of 305 ppm. This fluid was used to rinse the parts for re-assembly. The remainder of the fill fluid was essentially unchanged, from 304 ppm to 312 ppm, after being stored in a laboratory glass container for 16 months. This fluid was later used for filling the pump.

METSS HyTherm CI-2 pump inspection after two-years of storage

Disassembly and visual observations were similar to those after one year described above. Again no corrosion to any internal surfaces was noted and all parts had an appropriate new luster. The gel found was sampled and examined using Fourier transform infrared (FT-IR) spectroscopy and the spectrum is shown in Figure 1. This gel spectrum was very similar to the spectra of fresh METSS HyTherm CI-2 fluid indicating they were similar in composition. The gel tended to re-dissolve into the fluid when moved with a spatula. The pump was reassembled to proper specifications including internal lock-wire installation. Analysis of the fill fluid from the pump showed water content of 331 ppm. This fluid was used to rinse the parts for re-assembly. The remainder of the fill fluid measured 365 ppm, after being stored in a laboratory glass container for 9 months. This fluid was returned to 307 ppm, and then used for filling the pump for the final year of storage. Internal parts of the pump at this interval can be viewed in Appendix D.

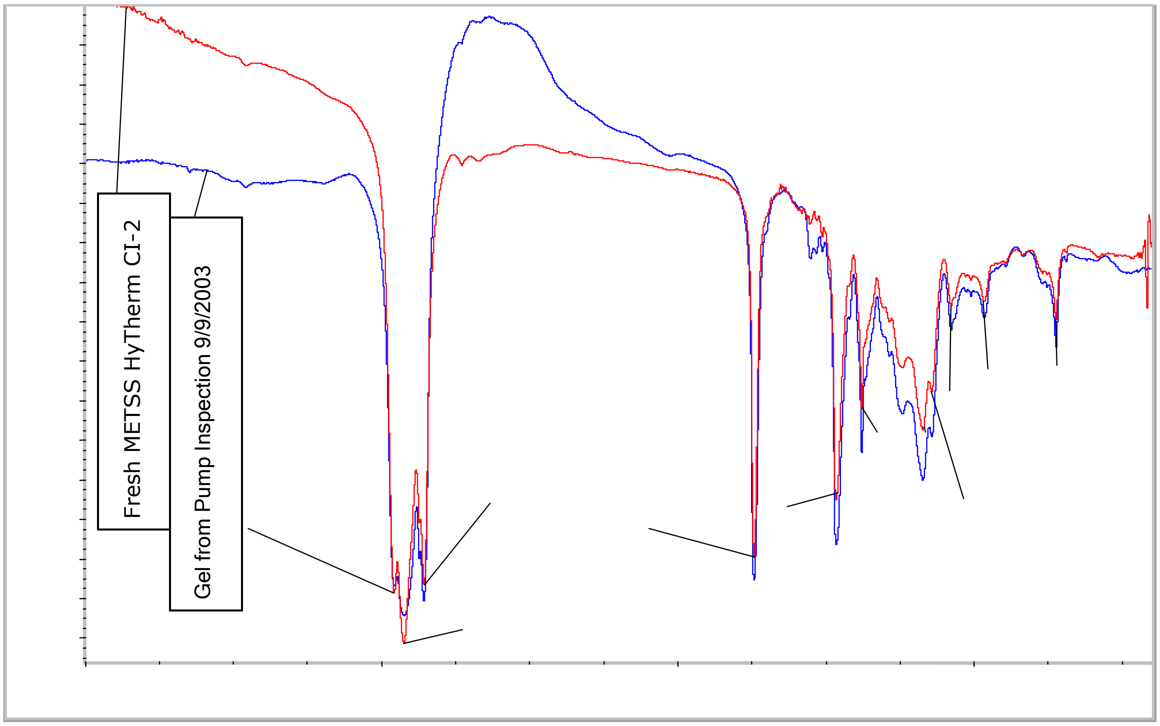

Figure 1. FT-IR plot of gel from METSS HyTherm CI-2 pump, obtained from the 2nd year pump inspection, versus fresh METSS HyTherm CI-2 fluid

<u>METSS HyTherm CI-2 pump inspection after three years of storage</u>

The third year inspection showed no notable changes in the pump internal surfaces when compared to the second year inspection. Photographs are in Appendix E.

Pump Test

After the completion of the third year of component storage, the METSS HyTherm CI-2 specimen pump was endurance tested using the method described previously. The following performance parameters were monitored during the pump test:

Flow Rates:	Pump outlet and pump case drain
Pressures:	Pump inlet and outlet, pump case drain, main filter inlet and outlet, case filter inlet and outlet, throttle valve outlet, heat exchanger inlet and outlet
Fluid Temperatures:	Pump inlet and outlet, pump case drain, throttle valve inlet and outlet, main filter inlet and outlet, case filter inlet and outlet
Torque:	Electric drive motor torque

This specimen pump exhibited the proper characteristics of a healthy and robust pump throughout the endurance period of 500 continuous hours. This pump performance was maintained without any degradation. The fluid samples drawn from the pump stand during the pump tests were analyzed per the ASTM methods in Table 2. These fluid samples indicated the METSS HyTherm CI-2 fluid continued to retain the original properties evaluated at the pump test start, as shown in Table 3. Post test teardown confirmed the impeccable condition of the pump, already demonstrated by the success of the endurance test. The internal parts displayed no visibly discernable wear and no corrosion. Many of the bronze alloy parts did not have the same brassy hue as a new pump, but a mild, violet tinting for unknown reasons. Photographs of the post-test pump parts are shown in Appendix F. The primary pump performance parameters proving proper function of the specimen pump are shown in Table 4.

DISCUSSION

The METSS HyTherm CI-2 fluid performed extremely well. The bearings and pistons stored in METSS HyTherm CI-2 exhibited no corrosion for the duration of the test. The only irregularities were gel formation in the stored pump and violet tinting on some bronze parts; both of which are not considered serious. It is probable that the rust inhibitor additive package is responsible for the violet tinting. Photographs of the gel can be found in Appendix G. This gel re-dissolved easily with mechanical actions and is therefore not expected to be a problem in aircraft operation. The METSS HyTherm CI-2 passed the 500 hour endurance pump test with no signs of wear.

Table 5 shows a comparison of the METSS HyTherm CI-2 with the other fluids that were tested and reported in “Study of Hydraulic System Component Storage with Operation and Rust-Inhibited Hydraulic Fluids” [7]. The METSS HyTherm CI-2 fluid performed equally or better than MIL-PRF-83282 and MIL-PRF-87257 operational fluids. Furthermore, Table 5 shows METSS HyTherm CI-2 offered superior protection against tarnish of 52100 steel during storage than the storage fluid MIL-PRF-46170, Type 2.

CONCLUSIONS

1. Bearings and pistons showed no corrosion after three years of storage in the METSS HyTherm CI-2, even in the presence of 400 ppm water contamination.

2. Pump testing demonstrated that storing and operating the pump with candidate fluid METSS HyTherm CI-2 had no adverse effects on the performance of the pump or the condition of the hydraulic fluid.
3. Endurance pump testing demonstrated the METSS HyTherm CI-2 is a fully functional hydraulic fluid and will be able to perform in the high temperature, high pressure environment of an aircraft hydraulic system.
4. Storing the pumps with operational fluid or candidate fluid METSS HyTherm CI-2 eliminates the high cost associated with disposing the barium containing rust inhibited fluid.

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The authors thank Mr. Charles Tobin and Mr. Timothy Reid of University of Dayton Research Institute, Dayton, OH for conducting laboratory fluid evaluations and Dr. Kenneth Heater and Mr. William Ricks of METSS Corporation.

Table 1. Bearing and Piston Jar Storage

Test Fluid	Estimated (actual) Starting H_20 ppm	Jar Contents	Year One	Year Two	Year Three
METSS HyTherm CI-2	400 (405)	Bearing & Piston	*	244 ppm	576 ppm
METSS HyTherm CI-2	400 (405)	Fluid Only	*	252 ppm	591 ppm
METSS HyTherm CI-2	400 (405)	Dip and Drain**	N/A	N/A	N/A

* Not measured

** Components soaked in fluid and drained for 10 seconds

Table 2. ASTM International Test Methods used to Determine Hydraulic Fluid Condition	
D 445	Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity)
D 664	Acid Number of Petroleum Products by Potentiometric Titration
D 892	Foaming Characteristics of Lubricating Oils
D 4172	Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method)
D 6304	Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fisher Titration
D 5185	Inductively Coupled Plasma Emission Spectroscopy (ICP)

Table 3. Characterization of Fluid Samples from METSS-Pump Test

Hours	KF Water (ppm)	Acid Number (mg KOH /gm)	Viscosity @ 40°C (cSt)	Particulate Contamination	Foam	Four-Ball Wear Scar (mm)	
				NAS 1638/ Boeing-Navy Class	Pass/Fail	Run 1	Run 2
Fresh	251	0.38	14.39	a	pass	a	a
0	277	0.46	14.56	6/3	a	0.38	0.38
118.4	327	0.41	14.97	a	a	a	a
118.9	322	0.37	14.92	a	a	a	a
206	316	0.34	14.86	5/2			
302	280	0.37	14.85	5/1	a	a	a
500	256	0.41	14.88	4/0	pass	0.43	0.43

a = Not determined

Table 4. Primary Performance Parameters Monitored During METSS Pump Test

TEST PUMP : **Eaton Aerospace Corp.**							PUMP TEST DATA FOR : **METSS HyTherm CI-2 Hydraulic Fluid**										
MODEL : **PV3-075-15**							AFRL/MLBT, WPAFB PUMP TEST STAND NO. 1										
S/N : **MX-350345**							TEST NO : **45**										
Hours	Torque (in-lbf)		Pressure (psig)				Fluid Flow Rate (GPM)				Fluid Temperature (°F)						
			Pump Inlet		Pump Outlet		Main		Case		Pump Inlet		Pump Outlet		Case Drain		
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
10.3	319	100	79	95	2864	2922	12.5	2.9	0.61	0.74	230	215	225	210	236	232	
162.4	319	85	80	97	2832	2815	12.4	3.4	0.63	0.98	230	218	235	222	240	235	
499.6	271	109	81	92	2840	2824	10.8	3.2	*	*	232	223	237	227	243	239	

A = Throttle Valve Open (High Flow); B = Throttle Valve Closed (Low Flow)
* = not measured due to sensor failure

Table 5. Results of Three Year Pump Storage Tests

Storage Fluid	Storage Year 1	Storage Year 2	Storage Year 3	Pump Stand Results
METSS HyTherm CI-2	No corrosion	No corrosion	No corrosion	Passed at 500 hours
MIL-PRF-83282	No corrosion	No corrosion	No corrosion	Passed at 511 hours
MIL-PRF-87257	No corrosion	No corrosion	No corrosion	Failed at 275 hours due to piston malfunction not storage fluid
MIL-PRF-46170	Tarnish on bearing balls	Increased tarnish	No corrosion	Not tested because MIL-PRF-83282 and MIL-PRF-87257 fluids did not cause failure

REFERENCES

1. MIL-PRF-83282, Hydraulic fluid, Fire Resistant, Synthetic Hydrocarbon Base, Metric, 30 Sept 1997.

2. MIL-PRF-87257, Hydraulic Fluid, Fire Resistant; Low Temperature, Synthetic Hydrocarbon Base, Aircraft and Missile, 22 April 2004.

3. MIL-PRF-5606, Hydraulic Fluid, Petroleum Base; Aircraft, Missile, and ordnance, 7 June 2002.

4. MIL-PRF-6083, Hydraulic Fluid, Petroleum Base, for Preservation and Operation, 17 September 1997.

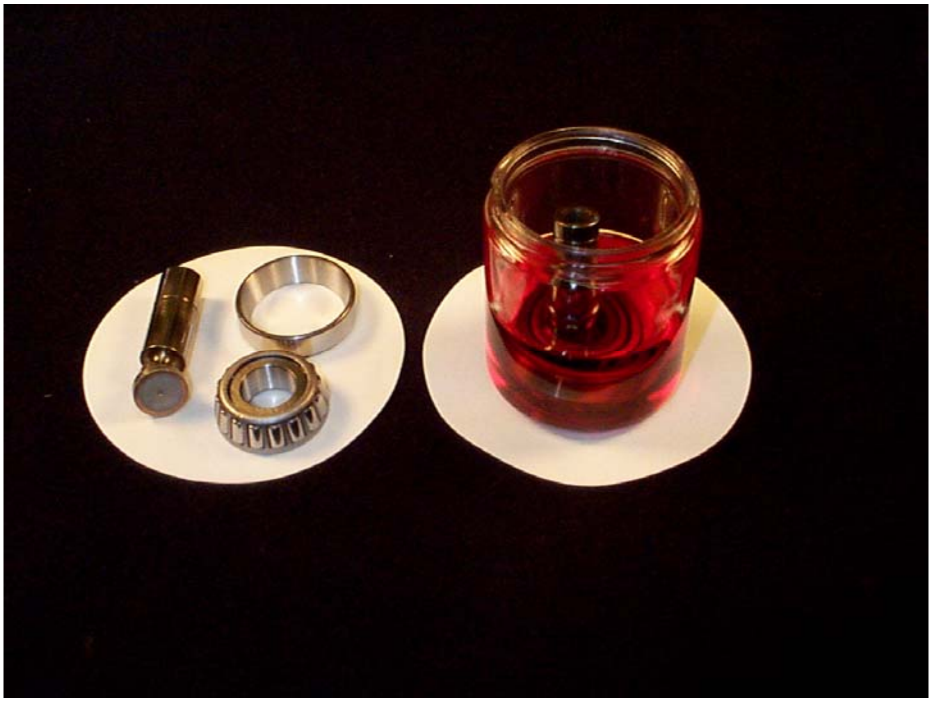
5. MIL-PRF-46170, Hydraulic Fluid, Rust Inhibited, Fire Resistant Synthetic Hydrocarbon Base, Type II, 19 January 2001. (Cancelled)

6. Stuck Servo valves in Aircraft Hydraulic Systems, S.K. Sharma, L.J. Gschwender, Carl E. Snyder, Jr., J.C. Liang, B.S. Schreiber, Lubr. Eng., 55, 7, (1999).

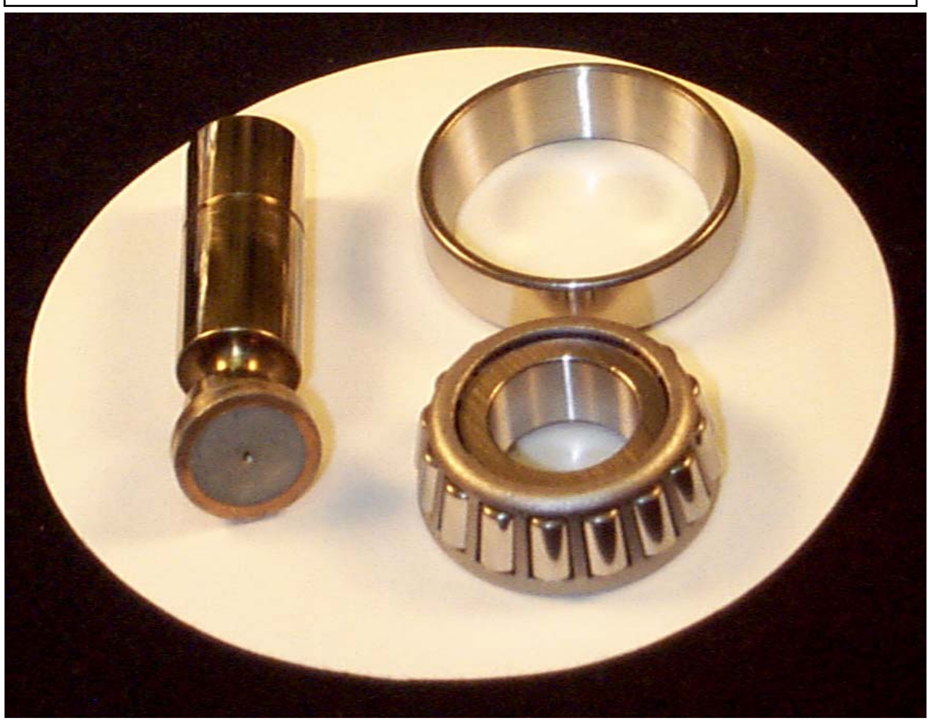
7. Study of Hydraulic System Component Storage with Operation and Rust-Inhibited Hydraulic Fluids", Lois J. Gschwender, Carl E. Snyder Jr., and Shashi K. Sharma, Tim Jenney, Angela Campo, Marcie B. Roberts, and George W. Fultz, Final Report for 01 Oct 1999 – 30 Sep 2004, AFRL-ML-WP-TR-2004-4279.

8. Military Aerospace Fluids and Lubricants Workshop Proceedings, AFRL-ML-WP-TP-2002-402, August 2002.

Appendix A
METSS HyTherm CI-2; Storage Jar Setup Photographs



Bearings and pistons shown in and out of a fluid filled storage jar.



A close up view of the bearing and pump piston

APPENDIX B
METSS HyTherm CI-2; Pre-Storage Photographs

Cylinder Block

Bearing, Pintle (SC = case drain side)

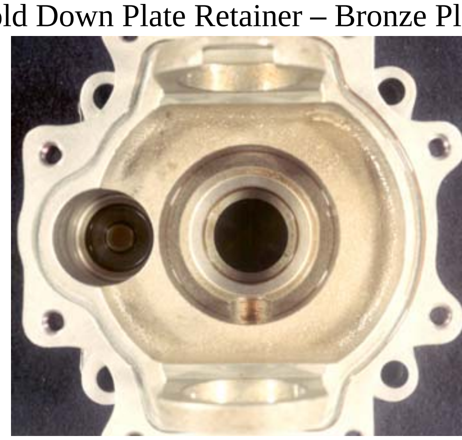
Piston Shoe Retaining Plate with Pistons

Pistons

Hold Down Plate Retainer - Steel

Hold Down Plate Retainer – Bronze Plated

Compensator



Housing

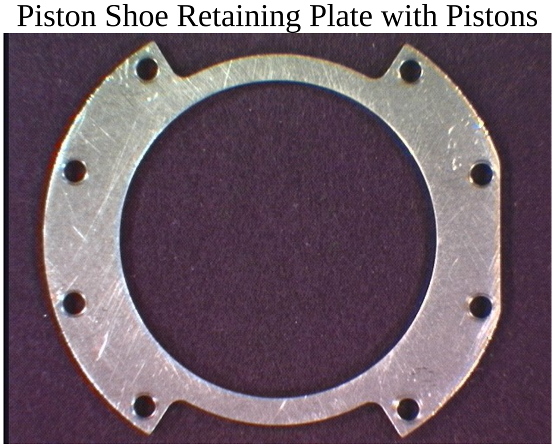
APPENDIX C
METSS HyTherm CI-2; One Year Storage Photographs

Cylinder Block

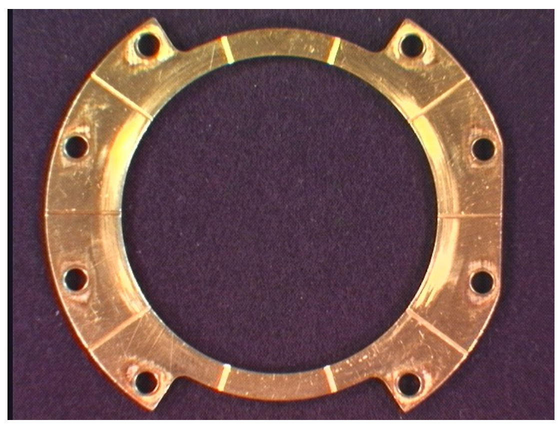
Bearing, Pintle (white = case drain side)

Piston Shoe Retaining Plate with Pistons

Pistons

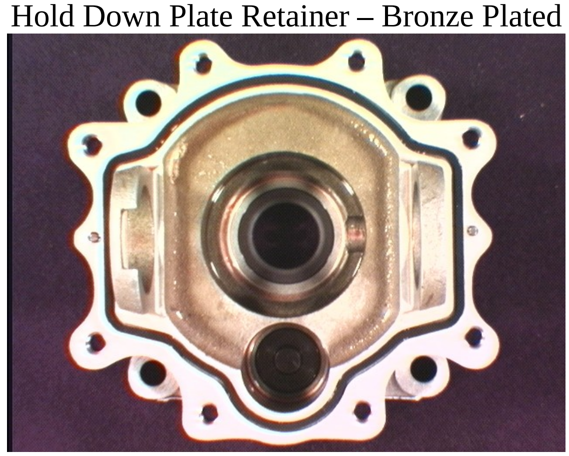


Hold Down Plate Retainer - Steel



Hold Down Plate Retainer – Bronze Plated

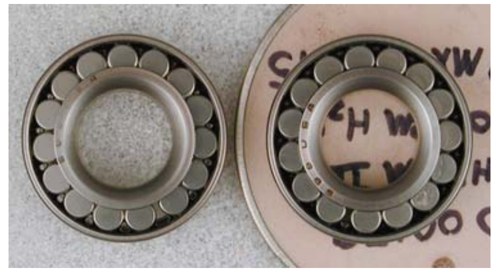
Compensator



Housing

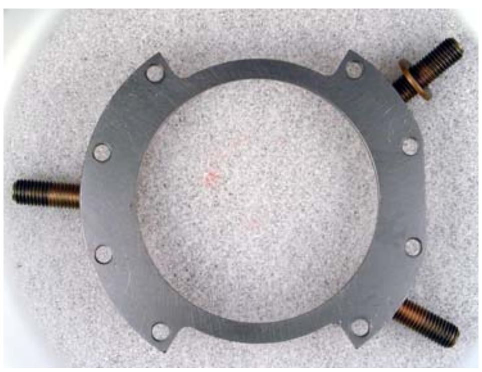
APPENDIX D
METSS HyTherm CI-2; 2-Years Storage Photographs


Cylinder Block


Bearing, Pintle. (pink identification tag denotes bearing from case drain side)

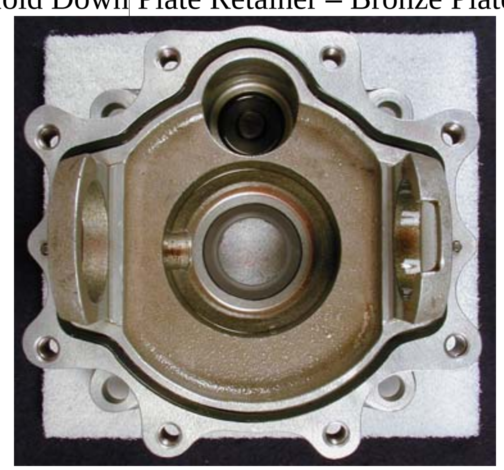

Piston Shoe Retaining Plate with Pistons


Pistons


Hold Down Plate Retainer - Steel


Hold Down Plate Retainer – Bronze Plated


Compensator


Housing

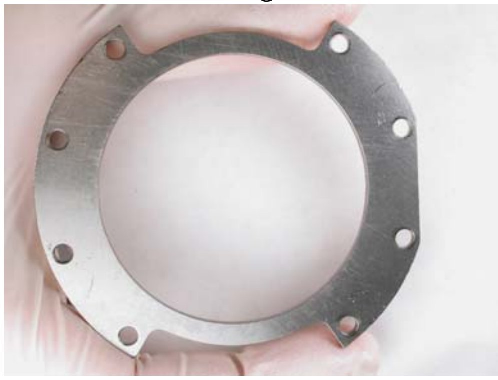
APPENDIX E
METSS HyTherm CI-2; 3-Years Storage Photographs

Cylinder Block

Bearing, Pintle. (CD = case drain side)

Piston Shoe Retaining Plate with Pistons

Pistons



Hold Down Plate Retainer - Steel

Hold Down Plate Retainer – Bronze Plated

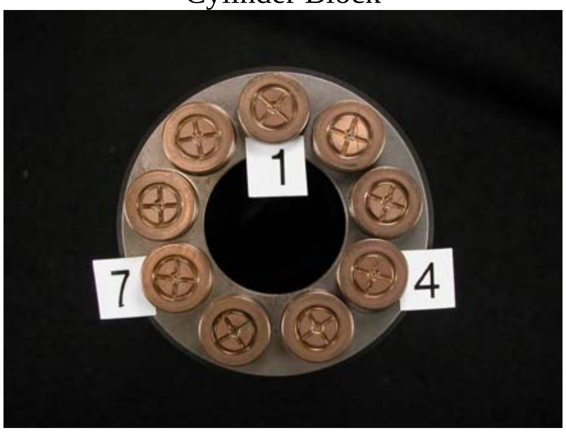
Compensator

Housing

APPENDIX F
METSS HyTherm CI-2; Post Pump Test Photographs

Cylinder Block

Bearing, Pintle (1 = case drain side)



Piston Shoe Retaining Plate with Pistons

Pistons


Hold Down Plate Retainer - Steel


Hold Down Plate Retainer – Bronze Plated

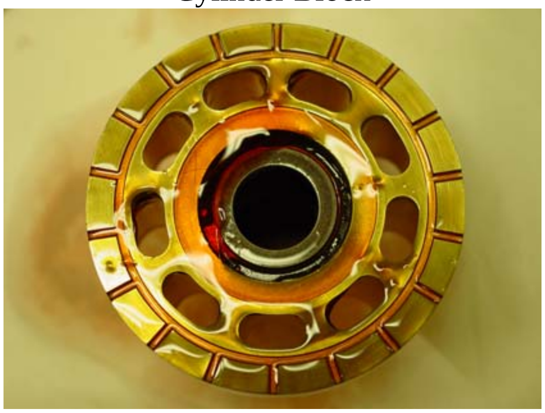

Compensator


Housing

APPENDIX G
METSS HyTherm CI-2 Gel; Post-Storage Photographs


Cylinder Block

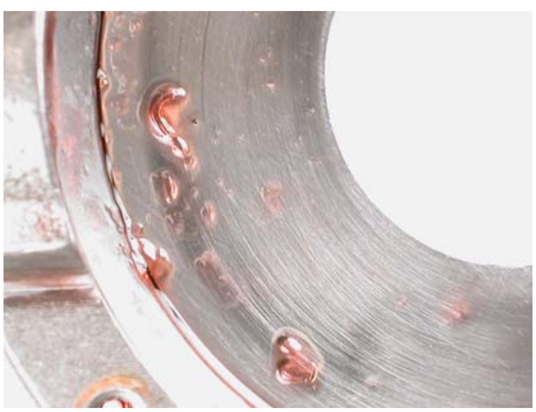

Cylinder Block


Cylinder Block


Pistons


Actuator Piston Cavity


Hold Down Plate Retainer – Bronze Plated


Yoke Bearing Plate Face

Bearing and Piston from Storage Jar Test